Understanding Direct Emission Measurement Approaches for Upstream Oil and Gas Production Operations

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INTRODUCTION

Breakthroughs in oil and gas extraction technologies are leading to greatly increased production activity in many areas of the United States (U.S.). Environmentally responsible development of this critical asset requires an understanding of the potential impacts of air pollutant emissions from upstream oil and gas production sites. These emissions can include volatile organic compounds (VOCs), which may impact regional ozone levels, hazardous air pollutants (HAPs) that could potentially create air quality concerns for near-site residents, and greenhouse gases (GHGs) such as methane (CH_4), a potent radiative forcing agent. A key to understanding emissions and mitigation options is in the development and optimization of cost-effective measurement methods specific to the upstream oil and gas production. Better measurements and models not only help protect the environment, but also help facilitate efficient resource development by alleviating concerns where appropriate.

Air emissions from oil and gas production sites vary based on a number of factors including the geologically-determined composition of the oil and gas product (wet or dry gas), age of well, production equipment designs, and equipment maintenance states. The U.S. EPA's mandatory GHG reporting rule[1] will greatly increase knowledge of GHG emissions from oil and gas production operations, but there is an ongoing need to improve emissions estimates, as well as to facilitate identification and remediation of compliance issues related to air quality. To improve both the measurement methods and emissions knowledge for this sector, the U.S. EPA Office of Research and Development (ORD), and its partners are investigating both on-site direct and off-site remote measurement approaches.[2]

This extended abstract describes a direct measurement study of production pad emissions in the Greeley, CO area conducted by ARCADIS in coordination with Sage Environmental Consulting (Sage) and in collaboration with several industry operators. The study focused on determination of instantaneous VOC and CH_4 emissions from production pads (with emphasis on oil/condensate tank emissions) using non-invasive measurement techniques. In addition to preliminary emissions results, this abstract describes the instrumentation used and issues encountered in the study.

BACKGROUND

In conjunction with a July 2011, EPA mobile measurement campaign in Weld County CO,[2] ARCADIS contracted Sage to perform on-site emission surveys at 23 oil and gas production pads in the area using previously demonstrated direct measurement and infrared camera

techniques.[3] The measurements were conducted in collaboration with three oil and gas companies that provided site access, process information, engineering descriptions, and safety oversight. The specific locations surveyed during the field study were determined prior to field deployment and were chosen to represent the range of operations (e.g. different gas qualities, condensate or produced water generation, etc.) present in the area and to maximize data collection efficiency. The identities of the companies and sites will remain anonymous for reporting purposes.

Emissions from production pads can be fugitive or vented in origin and for the purposes of this study, are grouped into four categories, tank emissions (three types) and non-tank emissions from auxiliary equipment(all other production pad emissions). As evidenced in recent measurement studies,[2,3] the most readily identified emission points by infrared camera observation are storage tank-related (i.e. leaking thief hatches). Atmospheric storage tank emissions (both oil/condensate and produced water) can be described as (1) tank breathing losses, that occur due to vapors produced by diurnal temperature changes, (2) tank working losses, that are caused by displacement during tank filling cycles, and (3) tank flashing losses, that occur when liquids with entrained gas experience a pressure drop during transfer of the liquid from a wellhead or separator. Of these four production pad emission categories (three tank and non-tank auxiliary), tank flashing losses are generally thought to be much larger than the others on an instantaneous basis. For this study, measurements from three of the four defined emission categories make up part of the data set (no tank working losses were observed). Emission measurements presented here represent "snapshots" in time. Because many production pad emissions (e.g. condensate tank flashing emissions) are short-term in nature, instantaneous emission measurements should not be extrapolated to tons per year values.

The air pollutant emissions from storage tanks can be mitigated in part by control devices, such as venting to flares, a technique typically employed in the Greeley, CO area. Although engineering calculations exist for estimation of tank emissions,[6,7] the effectiveness of controls due to engineering design variability, such as combustor back pressure, and maintenance-related variables such as thief hatch seal integrity, lead to uncertainty in actual emissions in comparison to estimates. Ideally a non-invasive, easy to execute quantification techniques could be used to produce reliable short-term emission measurements from these systems in order to increase emissions knowledge and compare actual emission to estimates.

The general goals for the study were to improve understanding component-level emissions and speciation profiles from production pads in the study area using non-invasive measurement approaches, such as infrared video and real-time leak measurements coupled with subsequent laboratory analysis of acquired canisters. Another goal of the study was to improve understanding of the performance of high volume sampling equipment[6,7] for emissions that are VOC rich (defined here as combustible vapor < ~95% CH_4). A final goal was to improve understanding of non-invasive measurement techniques for study of condensate tank flash emissions. Other studies[4,5] investigating flash emissions have performed measurements using installed vent flow meters and with techniques to seal leaks so as to force all flow through the measurement location. This study investigates the utility of a less invasive approach to investigate flash emissions using a high volume sampler described below. Because flash emissions occur at irregular intervals and are not sustained, they are challenging for short duration direct measurement approaches.   To help address this issue, the site operators manually induced flashing events, when deemed safe by the site operator and study personnel.

Experimental Methods

The production pad infrared (IR) video survey and emission measurement procedures are discussed briefly here and will be detailed in a future EPA report.[6] The methods are nearly identical to those used by Sage in execution of the site measurements portion of the City of Fort Worth Natural Gas Study.[3] For each well pad, a pre-measurement site survey was conducted that included collection of GPS and meteorological data, generation of a detailed inventory of all major on-site equipment, creation of a site sketch showing the location of all major components, and collection of several photographs of the site. After the pre-measurement data was recorded, a leak inspection survey of the site was conducted using a model GasFinderIR® video camera (FLIR Inc, Billerica, MA, USA). When an emission point was identified, the camera operator documented the type of equipment that was emitting and the location of the leak or vented emission and the video was saved.

Following the IR camera survey, a Bacharach Hi Flow Sampler™ (BHFS, Bacharach Inc. New Kensington, PA, USA) was used to determine the emissions rate from all safely accessible emission points identified by the survey (Figure 1). The BHFS is designed for measuring CH_4 leaks in downstream natural gas inspection and maintenance applications (in natural gas processing plants for example), but less is known about its use in upstream measurement applications on gas streams that can possess significant non-CH_4 components. The following description of the BHFS design and operation is based on the best information available at the time of publication.[8] The BHFS consists of an intrinsically safe, induced flow (blower) sampling system that pulls a certain volume of the emitted gas and surrounding air through a flexible hose into a manifold for analysis. The sample first passes through a flow restrictor where a pressure differential is measured and used to calculate the flow rate of the sample-air mixture. The BHFS automatically corrects the flow rates for difference in the density of air and CH_4. A portion of the sample is diverted to a combustibles sensor based on a dual mode catalytic oxidation/ thermal conductivity pellistor (e2v technologies ltd. Chelmsford, Essex, United Kingdom) to determine measured gas concentrations. A similar sensor is also used to determine the background combustibles concentration. In automatic mode, the sampler lowers the induced flow to 80% of the initial value and compares the calculated leak rate to provide confidence that the leak was captured in its entirety. Care is taken that the exhaust of the sampler does not impact the background sensor.

Figure 1: Example of a condensate tank vent measurement with a BHFS.

In this study, for low emission rates where vapor concentrations were below the detection limit of the BHFS, the concentration was determined with a Thermo Toxic Vapor Analyzer 1000B (Thermo Scientific, Franklin, MA, USA). For large emissions exceeding the BHFS's upper flow

range of 10.5 cfm, a bagging measurement was conducted using a three (3) standard cubic feet, anti-static measurement bag placed over the emission source (if conditions were deemed safe and the source was accessible) and its fill time was recorded.

For the BHFS measurements, the instrument-determined emission rate is calculated using Equation 1:

$$\textit{Emission (cfm)} = \frac{\textit{Emission \% - Background \%}}{100} * \textit{Flow (cfm)} \qquad (1)$$

Where:

        Emission (cfm)   = Flow rate of emission in cubic feet per minute
        Emission %   = Volume percent of combustibles in the sample stream
        Background %   = Volume percent of combustibles in the background sampling area
        Flow (cfm)   = Flow rate of sample and background air in cubic feet per minute

The BHFS response is calibrated at 2.5% and 100% CH_4 before each day's trials. As detailed in the results and discussion section, the translation of the BHFS from downstream natural gas inspection applications (where CH_4 dominates the emission speciation profile) to upstream applications on VOC-rich streams is not straightforward and the instrument-determined emission rate is now believed to deviate significantly from actual values under certain conditions.

In addition to BHFS readings, evacuated canister samples were collected at a select number of detected emission points at each site. Data from the canister samples in conjunction with the BHFS total flow results were used to compare with the volumetric emissions rate determined by the BHFS alone and also to estimate the mass emission rates of individual organic compounds from selected emission points. The samples were collected directly from the exhaust port of the BHFS during sampling, using a 6 liter SUMMA canister. The sample collection integration time was approximately 30 seconds. Canisters were generally collected at the largest emission point at each site, determined by the BHFS emission flow rate (cfm). A total of 33 canisters were acquired at the 23 sites. At least one canister was acquired at each site. The number of canisters at each site was dependent on and the amount and severity of emission points detected. The canisters were analyzed for the US EPA Photochemical Assessment Monitoring Stations (PAMS) Target Volatile Organic Compounds (VOC), as well as percent level CH_4, ethane, ethene, propene, and propane by ASTM D1946/D1945.

Calculation of a emission rate of total combustibles (all canister-measured compounds) or total VOCs (all compounds excluding CH_4 and ethane) using canister information was accomplished by summing the concentrations of individual measured species to achieve a total measured pollutant volume percent which was then multiplied by the total BHFS gas flow rate (converted to standard conditions). This canister-based emission rate is a modified version of Eq. (1) where the pollutant concentration is determined by the canister instead of the BHFS combustibles sensor.

Calculation of speciated mass emissions from the canister data was accomplished by first converting the VOC concentration results from ppmv to units of mg/m^3, and converting the BHFS gas flow rate to standard gas flow. The VOC emission rate is calculated using Equation 2:

$$ER = C * CFMstd * CF * 8760 \qquad (2)$$

Where:

ER = VOC Emission Rate (lb/year)

C = VOC Concentration (mg/m^3)

$CFMstd$ = Flow rate (ft^3/min) corrected to standard conditions

CF = Units Conversion Factor = 3.75 E-06 (1 m^3/35.32147 ft^3) *60 minutes/hour
* (1 lb/453592.37 mg)

Field data were collected electronically on data loggers and archived daily at the end of testing. Further information on procedures is contained in references 3 and 6.

Results and Discussion

A total of 23 sites were surveyed, excluding two replicate site visits. The average production pad consisted of five wells, 258 valves, 2,583 connectors, three condensate tanks, one produced water tank, four thief hatches, five pressure relief devices, three separators, and all sites contained one flare/combustor. One production pad contained a dehydration unit, and four each contained one vapor recovery unit. Reference 6 contains engineering details of each production

Figure 2: BHFS volumetric emission rate readings by component group: (-) individual readings, (o) mean, (¨) median, bars represent ± 1s. Inset labels (A-G), see Figure 3.
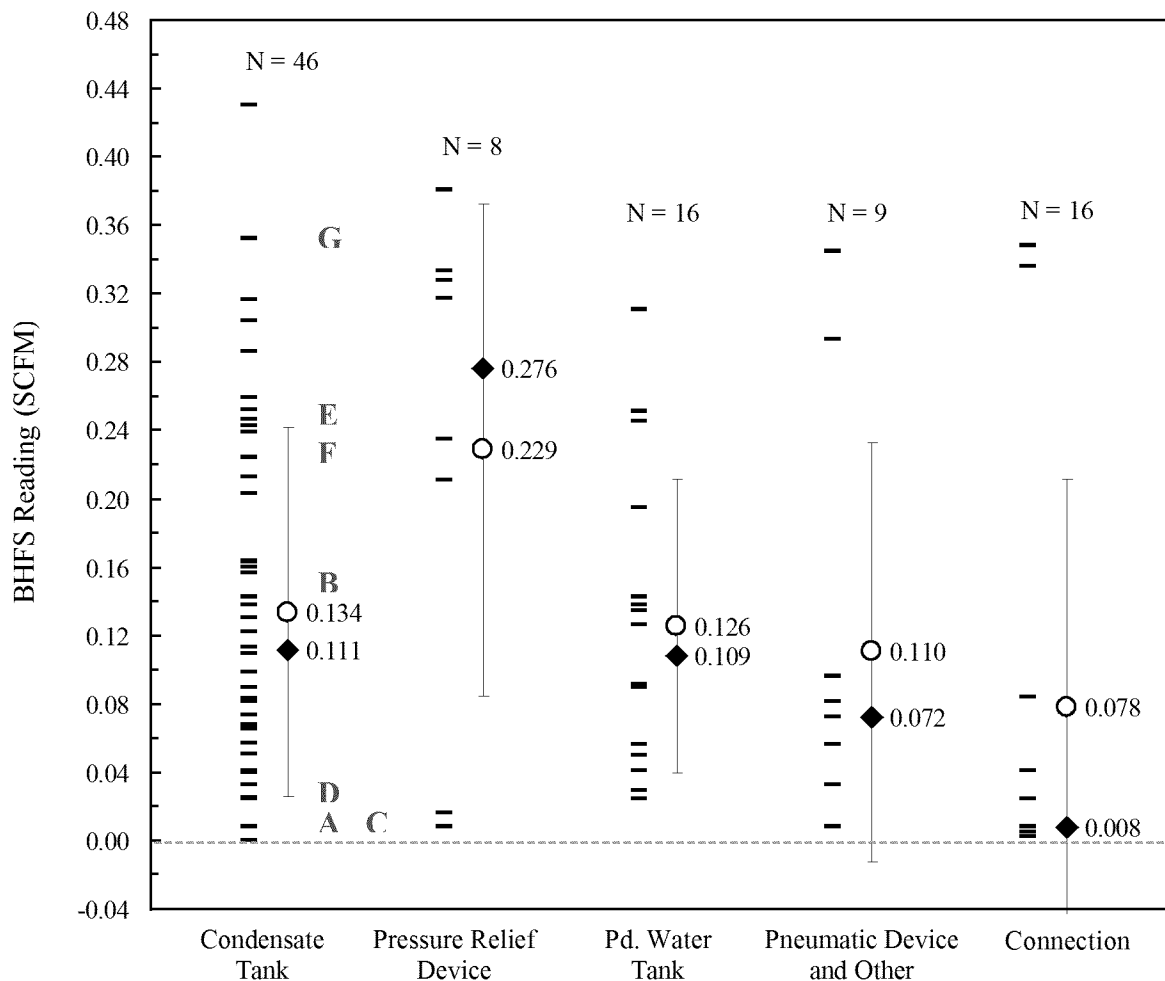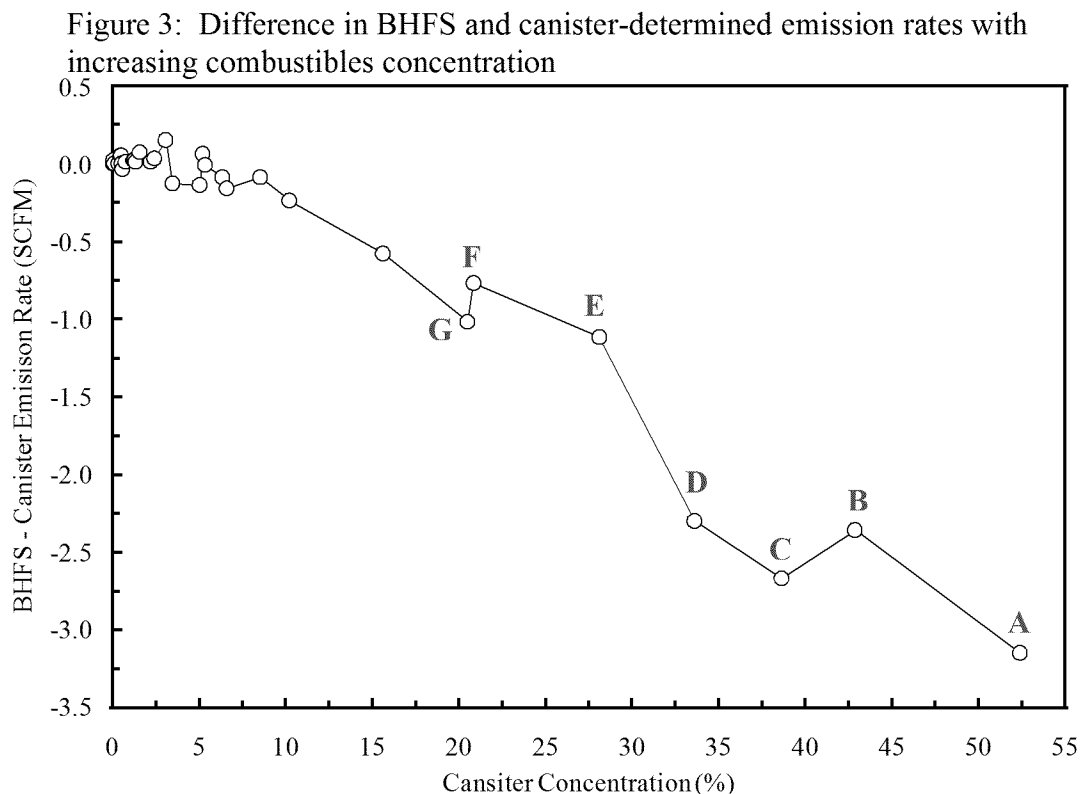
pad visited along with a layout sketch of each site. Of the 23 sites surveyed, 19 processed field gas by a single stage three phase separator and four utilized a two stage separation process to further recover natural gas by reducing the net pressure by approximately one fourth of the liquid sent to the condensate tanks via a buffer tank.

Each emission that was detected with the IR camera (93 total) was measured with the BHFS to determine the BHFS volumetric leak rate of the mixed vapor stream. The average emission rate determination for five major component grouping is shown in Figure 2. Condensate tank emissions were identified as leaking thief hatches (N=44) and vent structure (N=2). All measurements in the pressure relief device category came from condensate tank emissions. Thirteen of the produced water tank measurements were from vents with two described as hatches and one as a cover. Emissions from five pneumatic control devices were measured with "other" category consisting of one valve, two equipment vent devices. The remaining two measured emissions in this category came from a vapor recovery unit knock-out pot (0.34 SCFM) and a leaking compressor filter (0.294 SCFM). The final category represents all miscellaneous connections and fittings observed to be leaking. As similarly observed in other studies,[2,3] leaking thief hatch seals on condensate tanks was the most frequently observed production pad emission category. The difficulty in maintaining seal integrity is readily acknowledged by industry collaborators for this study. Additional details on emissions from various component types with associated IR video examples will be included in the presentation. The inset labels in Figure 2 (labels A-G), associated with the condensate tank emissions, are present to reference specific measurements described in Figure 3.

As discussed in the experimental methods section, the BHFS is calibrated to CH_4 and the volumetric emission determination is believed to be relatively accurate for measurement of emissions within its operational range that are primarily composed of CH_4 (i.e. combustibles > ~95% CH_4). Emissions from well pads in Weld County Colorado have high VOC to CH_4 ratios due to the wet gas nature of the production in this area (in contrast to Fort Worth, TX).[3] This difference is particularly exaggerated for this study since a large percentage of the measurements came from condensate tank emissions. It is hypothesized that because the BHFS utilizes a dual mode catalytic oxidation/ thermal conductivity sensor to determine combustible gas concentrations, measurements of sample stream gases with different physical properties than CH_4 will affect various aspects of the operation of the BHFS. The primary effect is found to be in the vapor concentration determination used in Eq 1. Flow rate bias due to density differences of the sample stream relative to CH_4 are also likely present but are not discussed here.

As determined by canister analysis (discussed subsequently), the typical hydrocarbon profile varies by source (i.e. condensate tank compared to non-tank) but is dominated by aggregate non-CH_4 species (ethane, propane, butane, etc) for this study (in contrast to profiles from dry gas fields).[3] For this study, when sampled combustibles concentrations exceed ~ 10%, (caused by low dilution through the BHFS), the BFHS determined volumetric emission readings can be biased low (Figure 3). The ordinate of Figure 3 shows the difference in the BHFS determined volumetric emission rate (called BHFS) and that found by combining the canister-derived total combustibles concentration with the BHFS total flow rate (called canister), plotted against the total combustibles percent by volume in the canister (abscissa). At up to » 5% combustible concentration by volume, the BHFS's sensor is believed to operate in catalytic oxidation mode then, as the concentration increases, the oxidation is saturated and the sensor switches to thermal conductivity mode. The unit's response is calibrated at 2.5% (mid range of the catalytic

oxidation mode) and 100% CH$_4$ before each day's trials. Since the relative thermal conductivity of CH$_4$ compared to air is significantly higher than that of other observed hydrocarbons (at the pellistor's operating range around 500 C), the concentration reading (and hence leak rate

Figure 3: Difference in BHFS and canister-determined emission rates with increasing combustibles concentration

determination) of the BHFS underestimates actual by progressively larger amounts with increasing total concentration of non-CH$_4$ combustibles. This situation occurs for larger leaks but is also affected by the coupling of the extraction system which controls the dilution of the vapor stream.

The underestimation of the volumetric emission rate in these cases can be very significant as evidenced by the inset labels (A-G) of Figure 3 that link the largest absolute difference measures (BHFS - Canister results) to the BHFS determined values shown in Figure 2. It is the case that among the lowest measured values with the BHFS were some of the highest actual emissions. In fact, cases A, C, and D, were condensate flash emission events, which are known to greatly exceed breathing emissions on a short time duration basis. It is believed that this underestimation in the volumetric emission response of the BHFS is due mostly to the aforementioned concentration determination issues caused by the thermal conductivity differences found in VOC-rich streams, but may also be due in part to internal flow rate density compensation issues that arise from non-CH$_4$ emissions. These factors are the subject of further investigation. Regardless of cause, this low bias can be reduced through additional dilution of the sampling stream (increasing clean air flow). This would however further limit the useful range of the instrument (currently 10.5 CFM maximum total flow rate) so alternative measures, such as calibrated leak bagging, become more attractive.[6,7]

Methane and VOC mass emission rate estimates were produced for a subset of observed leaks (N=33) using the previously described procedure which combines the BHFS total flow and

canister analysis (Figure 4). The VOC emission values represent the summation of 55 canister measured compounds that were above detection limit (excludes ethane and methane). All measurements were either associated with a condensate tank emissions or one of five non-tank related emissions sampled (two separator, two well head and one dehydrator). The speciation profiles for the tank and non-tank emissions were very different. A measure is found by calculating the volumetric ratio of CH_4 to the summation of other measured compounds (VOCs plus ethane) which yields values 243.3% ($s = 161.3\%$) and 38.3% ($s = 26.8\%$) for non-tank and tank related emissions respectively. It is noted that one produced water tank is included in the tanks set which possessed amongst the lowest CH_4 ratios (17.2%). Twenty five of the tank-related canisters were acquired during thief hatch measurements with three from pressure relief or vent devices. The latter subset showed an average CH_4 ratio of 20.3% ($s = 6.8\%$). The CH_4 ratio difference between the tank-related and non-tank related emissions is evident in Figure 4b which shows very low non-tank related VOC emissions. Five tank canisters were identified as being acquired during flash emissions and these samples showed CH4 to VOC ratios similar to the full set (39.6%, $s = 35.1\%$). VOC emission measurements associated with these five flash canisters were (2.31 g/s, 1.59 g/s, 1.50 g/s, 0.20 g/s, and 0.02 g/s). The last of these values is believed to be unrealistically low and is the subject of further investigation. Data at this point is considered preliminary and is subject to revision.

SUMMARY

Improved understanding of both air pollutant emissions from oil and gas production operations and accuracy of the tools we use to measure and model these emissions is important for environmentally responsible development of this national asset. This extended abstract presents preliminary information from a direct measurement study of production pad emissions near Greeley, CO, conducted by ARCADIS in coordination with Sage Environmental Consulting and in collaboration with several industry operators. The goals of the study were to improve understanding of component-level emissions, speciation profiles, non-invasive measurement approaches, and condensate tank flash emissions. In addition to preliminary emissions results, this abstract describes the instrumentation used for data collection and methods used for emissions quantification. Next steps include continued processing of this data set to better understand instrument performance, measurement uncertainty, and source emissions. Additionally, recommendations for next steps in laboratory studies, field testing, and method development activities for sector specific non-invasive measurement approaches will be formulated.

Figure 4: (a) CH_4 and (b)VOC Mass emission rate by canister calculation: (-) individual readings, (o) CH_4 mean, (¨) CH_4 median, (□) VOC mean, (▲) VOC median, bars represent ± 1 s.
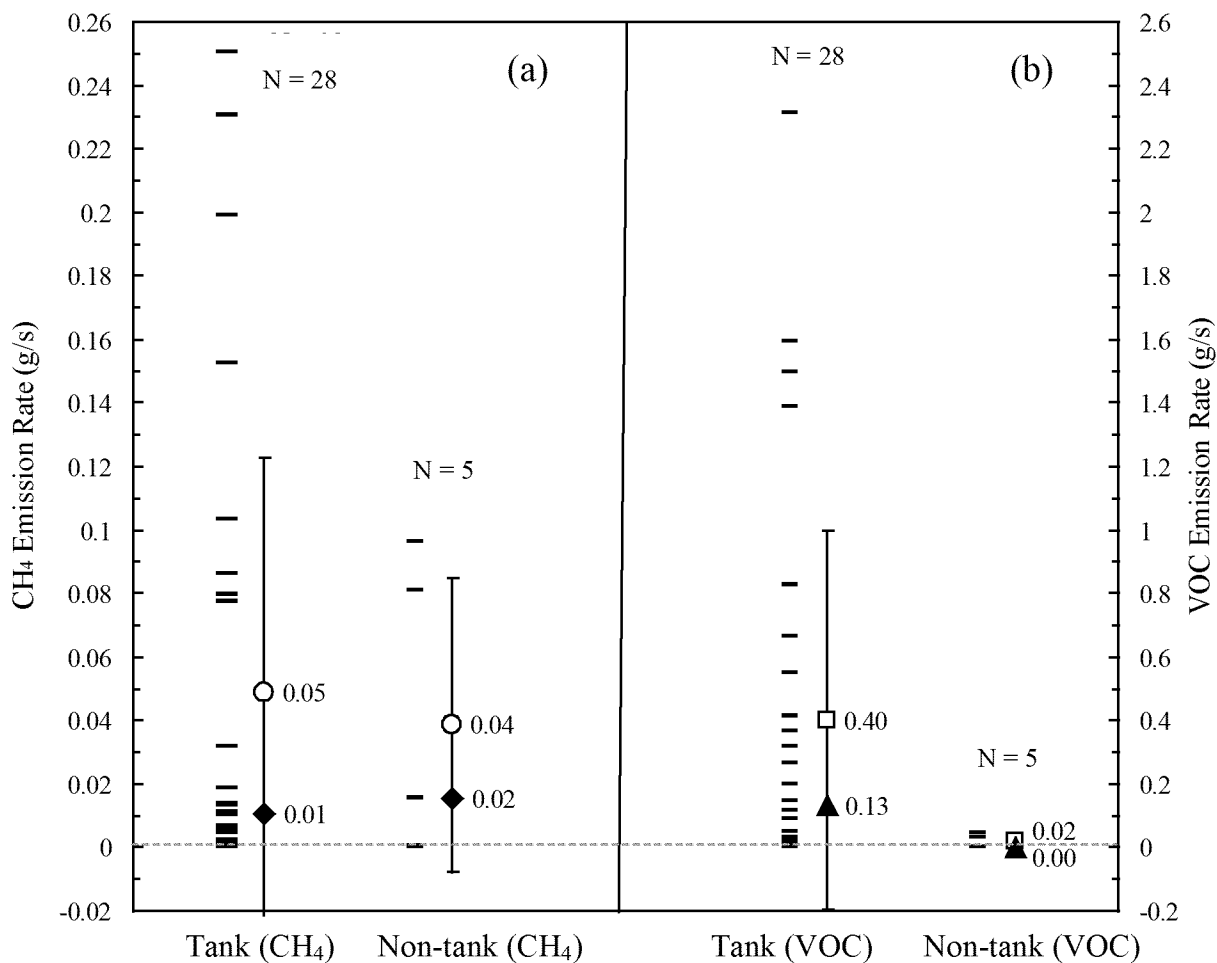
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9

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8. Descriptions of the Bacharach Hi Flow Sampler[TM] design and operation limits are based on best available information including discussions with the manufacturer and the distributor of the instrument. This abstract is being communicated to the distributor and manufacturer and any corrections will be noted in presentation and full EPA report. Any misrepresentation is unintentional.

KEYWORDS

oil and gas production, fugitive emission, direct measurements, methane, VOC, HAP, GHG,